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Evolution of concepts for the geothermal projects in the Upper Rhine Graben

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Introduction

The Upper Rhine Graben (URG) is a geological structure from the European Cenozoic Rift System. It is characterized by a series of thermal anomalies interpreted as the signature of large scale natural brine advection occurring inside a nearly vertical multi-scale fracture system cross-cutting both deep-seated Triassic sediments and Paleozoic crystalline basement (Baillieux et al., 2013; Pribnow and Schellschmidt, 2000; Schellschmidt and Clauser, 1996). Sedimentary formations of the URG host oil fields widely exploited in the past which exhibit exceptionally high temperature gradients. Thus, geothermal anomalies are superimposed to the oil fields (Figure 1). Since the last 35 years, geothermal projects were developed in France, Germany and Switzerland in order to exploit deep geothermal energy.

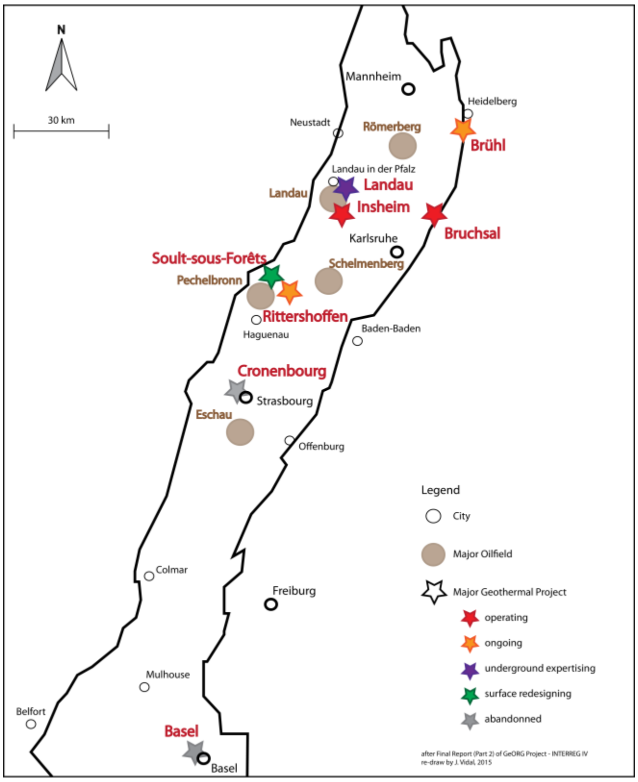

Figure 1 Deep geothermal projects in the URG

Concept evolution

The first geothermal well in the URG was drilled in 1984 at Cronenbourg (Alsace, France) in order to explore the geothermal potential of the sandstones from Buntsandstein (Lower Trias) (Housse, 1984). The productivity of the well was however too low for setting an economically viable geothermal loop but hydraulic testing showed that the natural permeability was higher into localized fracture zones than into the matrix. Accordingly the matrix flow concept was shown to not be effective for deep geothermal exploitation in URG. The pilot geothermal project of Soultz-sous-Forêts (Alsace, France) was launched in order to create a deep granitic reservoir based on the Hot Dry Rock (HDR) concept (Gérard and Kappelmeyer, 1987). The HDR concept is a concept initiated in Los Alamos (USA) and Cornwall (UK) for exploiting the vast energy resource that resides as heat in the low-permeability rocks which underlie most continental regions at practically-drillable depths. In 1987, the exploration well was drilled down to 2000 m depth (Figure 2) and reveals brine circulating into hydrothermally altered fracture zones at the top of the basement. The exploration well was deepened and three other wells were drilled down to 5000 m depth between 1992 and 2004 (Figure 2) (Dezayes et al., 2005). The deep granitic reservoir shows a lower fracture density associated to a low index productivity that was not improved by the performed hydraulic operations. The HDR was progressively abandoned for the Enhance Geothermal System (EGS) technology that consists to stimulate existing fractures of the reservoir to improve their natural permeability. Projects based on lessons learned from Soultz were developed in the URG using the EGS concept (Figure 1) such as at Landau (Baumgärtner et al., 2005; Hettkamp et al., 2013) and at Insheim (Baumgärtner and Lerch, 2013) (Baden-Württemberg, Germany), at Brühl (Lotz, 2013; Melchert et al., 2013) (Rhineland, Germany) and at Rittershoffen (Baujard et al., 2014) (Alsace, France). Some wells in the URG did not required EGS technology to improve the connection with the reservoir for an industrial economic application. They are considered as hydrothermal systems.

Figure 2 Chronology of the deep geothermal projects and their associated wells in the URG

Exploration phase

For the project of Cronenbourg, a seismic reflection campaign was done to image the sedimentary cover (Housse, 1984). At Soultz-sous-Forêts, seismic reflection data in the sedimentary part were reinterpreted in order to identify accurately the sedimentary formations that will be cross cut by drillings before the basement (Gérard and Kappelmeyer, 1987). These pioneer projects targeted geological hard rock formations whereas recent projects rather targeted the fracture network at the sediments-basement interface in order to reactivate it. Thus, seismic reflection campaigns were performed to image faults that are potential permeable drains for geothermal resource. The major drawback is that 2D seismic does only image the sedimentary cover. Major faults that cross cut the sedimentary cover in seismic interpretation and are extended into the basement. The method to extend the faults in the basement is uncertain because the relationship between the fracture network geometry and the present day stress field is not necessarily similar between the sedimentary and the basement. Experience of 3D seismic for the project in Brühl showed promising results to identify the geometry of faults at the sediments-basement interface (Lotz, 2013). The evolution of concept in geothermal projects carries a need for technical innovation in exploration methods in order to accurately characterize the fracture network at the top of the basement.

Geothermal target

In the URG, faults dip highly and drilling vertical wells present a high probability to not cross these highly dipping faults. The recent wells in the URG are deviated in order to intersect a maximum of nearly vertical faults and fractures. A deviated well is more complicated to drill and to log and thus more expensive. Insofar the cost of the drilling is exponential to the drilled length, the recent wells are not drilled into the deep granitic basement like in Soultz-sous-Forêts but target the fracture network at the sediments-basement interface (Figure 2). Geothermal resource circulation at this interface is visible on temperature profiles of the geothermal wells when the conductive thermal regime transits to a convective thermal regime with a slope change on thermal profiles (Schellschmidt and Clauser, 1996). On Figure 3, the slope change matches in depth for thermal profiles for several deep geothermal projects of the URG and the top of the convection corresponds to the Buntsandstein (Early Triassic) sandstones and the top of the granitic basement. They are brittle formations affected by fractures through which natural brine circulates (Dezayes et al., 2010; Vidal et al., 2015).

Figure 3 Thermal profiles in the deep geothermal projects in the URG and their associated geology. Thermal profiles of GCR-1, GB-2, Gt La1 and GT-1 are approximations of field data.

Reservoir development

Hydraulic stimulation of the granitic reservoir below 4.5 km depth for the second geothermal of the triplet (GPK-3) at Soultz and for the first well of the Deep Heat Mining (DHM) project in Basel induced seismic events of magnitude M=2.9 and M=3.4, respectively (Cuenot et al., 2008; Häring et al., 2008). These micro-seismic events were felt by population and led to the abandon of the DHM project. At Soultz, chemical stimulations of the crystalline basement were favored instead of hydraulic stimulation because they cause a lowest number of micros-seismic events than the hydraulic one (Nami et al., 2008; Portier et al., 2009). From these chemical stimulations, well injectivity or productivity has been improved by a significant factor ranging between 1.12 and 2.5. Stimulation programs for recent projects were based on combined thermal, chemical and/or hydraulic stimulation. At Rittershoffen, hydraulic stimulation was performed into the first well after chemical stimulation with a moderate injection pressure in order to avoid significant induced seismicity possibly felt by the nearby population (Vidal et al., 2014). Chelating biodegradable agents that are environmentally friendly were used for the first time at Rittershoffen to dissolve fracture fillings instead of conventional acid which improved the injectivity by a factor 1.70 (Recalde Lummer et al., 2014). To prevent the waste of acid fluids in high permeability zones, packers and coiled tubing are very used to stimulate localized zones. Geothermal wells in Insheim, Landau, Brühl and Rittershoffen did not request stimulation operations because they presented a sufficiently high natural permeability for industrial exploitation. These cases are very positive in terms of costs and public acceptance for geothermal projects.

However microseismicity might also happen during exploitation such as at Landau during August 2009 when a seismic event of magnitude M=2.7 happened and was felt by population (Abschlussbericht der Expertengruppe, 2010). At Soultz, micro-seismic event of magnitude M=2.3 happened during the 2011 hydraulic testing phase but was not felt by the population. Several hydraulic tests at Soultz show that the splitting of the reinjection between two wells in order to reduce the reinjection pressure decreases the microseismicity (Cuenot and Genter, 2015).

Conclusion

Since matrix flow project in sandstones and HDR project in deep granitic basement, the concept evolved towards the EGS project that aims at developing a deep geothermal reservoir into a natural fracture network. EGS is based on thermal, chemical and hydraulic stimulations in order to reactivate preexisting fractures and connect them to a large-scale fractured reservoir. Recent wells in Rittershoffen, Brühl or Insheim were not stimulated and presented a sufficient natural permeability for industrial exploitation. They are classified as hydrothermal and not EGS wells. Their trajectories were well designed according to the geologic and structural context and they crossed cut several permeable fractures. The absence of stimulation is a substantial advantage for public acceptance of future geothermal projects.

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